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Device behavior of an In/p-Ag(Ga,In)Te_2/n-Si/Ag heterojunction diode

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ABSTRACT

In this work, p-(Ag–Ga–In–Te) polycrystalline thin films were deposited on soda-lime glass and n-type Si substrates by e-beam evaporation of $AgGa_{0.5}In_{0.5}Te_2$ crystalline powder and the thermal evaporation of Ag powder, sequentially in the same chamber. The carrier concentration and mobility of the Ag–Ga–In–Te (AGIT) film were determined as 5.82×10^{15} cm^{-3} and 13.81 cm^2/(V s) as a result of Hall Effect measurement. The optical analysis indicated that the band gap values of the samples were around 1.58 eV. The structural analysis was carried out by means of X-ray diffraction. Current–Voltage (*I*–*V*) measurements depending on the sample temperature were performed to investigate the device characteristics and the dominant conduction mechanism in an In/p-AGIT/n-Si/Ag structure. The series and shunt resistances were calculated by the help of parasitic resistance analysis as 5.73 and 1.57×10^4 Ω cm^2, respectively at room temperature. The ideality factors and barrier heights were evaluated as a function of sample temperature. In the low bias region, the thermionic emission together with the generation–recombination mechanism was investigated as the dominant transport mechanism; however, in the high bias region, space charge limited current was analyzed as the other effective mechanism in the carrier conduction. The built-in potential of the device was also determined by the help of capacitance–voltage measurements.

1. Introduction

Thin film photovoltaic device technology is low cost alternative to the traditional silicon-based solar cells, which is offering large scale material usage. Moreover, there has been a great deal of interest in the study of the chalcopyrite semiconductors in this technological point of view. Especially, ternary and quaternary chalcopyrite compounds based on the combinations of I, III and VI groups of elements have taken considerable attention because of their tunable optical and electrical characteristics [1]. High absorption coefficient and suitable band gap values make these compounds promising materials for absorber layer in solar cell applications. Therefore, these chalcopyrite absorbers are quite favorable for the production heterojunction and tandem systems [2]. The polycrystalline I–III–VI_2 chalcopyrite compound thin films, especially $CuInSe_2$ (CIS) [3] and their quaternary counterpart Cu(In,Ga)Se_2 (CIGS) [4] are taking considerable attention for the next generation photovoltaic devices [5]. Thin-film solar cells with CIGS module applications reach the highest photovoltaic conversion efficiency [6]. However, Cu based compounds causes shorting effect in photovoltaic devices due to its larger diffusion coefficient

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and there are many works to overcome these obstacles for thin film structures [7]. Therefore, other chalcopyrite materials having very similar electrical and optical properties became popular [8]. Among the several materials of this group, $AgInTe_2$ (AIT) and $AgGaTe_2$ (AGT) have proved to be stable and efficient absorber materials for polycrystalline thin film heterojunction solar cells [9–13].

In this work, we focused on the quaternary system Ag–Ga–In–Te (AGIT) since it allows tailoring of the optical band gap and other properties. This system is located between direct band gap the ternary semiconducting chalcopyrite compounds AIT and AGT. Very little work on AGIT thin films has been reported. The physical properties of the chalcopyrite semiconductor AGIT has confirmed its potential for various thin film applications [14–16], but as far as it is known there is no such a work published on the device characteristics of this structure. Therefore, to understand and get the information about the device behavior and properties of p-AGIT thin films, the p-AGIT was deposited on n-Si wafer and soda lime glass substrates. Device characterization of In/p-AGIT/n-Si/Ag structures was investigated. This study can be a guide for future studies about the photo-voltaic device applications of AGIT chalcopyrite material.

2. Experimental details

AGIT thin films were deposited on soda-lime glass and mono-crystalline n-type Si (111) wafers having the resistivity 1–3 (Ω cm) substrates to produce a p-AGIT/n-Si heterojunction structure. Thin film deposition was carried out in a system including e-beam and thermal evaporation facilities in the same chamber. The stoichiometric high purity Ag, Ga, In and Te elements were sintered in an evacuated quartz ampoule in a vertical furnace at 1050 °C for 2 days. Then, the pre-sintered quartz ampoule was placed to a Crystalox MSD-4000 model three zone vertical Bridgman–Stockbarger system and a special temperature profile was used to obtain the single crystal $AgGa_{0.5}In_{0.5}Te_2$ compound. The temperatures of three zones of furnace were adjusted to the values of 1100, 800, and 600 °C, respectively and following to a 72 h of translation from top to bottom zone with a translation speed of 1.0 mm/h.

$AgGa_{0.5}In_{0.5}Te_2$ crystal powder was crunched in the fine grains before used as the evaporation powder. The surface of the wafers was subjected to a cleaning procedure with HF: H_2O = 1:10 solution in order to remove the native oxide layer and then rinsed in deionized water consecutively blown dry in N_2. During the deposition process, successive layer by layer deposition method were used to get a stoichiometric and homogenous film structure by using $AgGa_{0.5}In_{0.5}Te_2$ and high purity Ag powders as the evaporation sources of e-beam and thermal evaporations, respectively. The substrate temperature during deposition was kept at around T_S = 200 °C and the thickness of the samples controlled and monitored in-situ by Inficon XTM/2 deposition monitor. Before starting the deposition process, the back surface of the n-Si wafer was coated with Ag by thermal evaporation, as a back ohmic contact, and annealed at 450 °C under the nitrogen atmosphere to enhance the ohmicity of the contacts. The fabrication of the p-AGIT/n-Si heterojunction structure was completed after the deposition of the transparent indium front contact by the thermal evaporation using the dot-patterned copper masks. Again, following to In contact deposition, the samples were annealed at 100 °C under the nitrogen atmosphere to improve the contact behavior. The thickness of the films was measured electromechanically following to the deposition by Vecoo Dektak 6 M thickness profilometer and it was around 385 nm. The compositional analysis of the samples was carried out by means of a JSM-6400 Scanning Electron Microscope (SEM), equipped with NORAN System 6 X-ray Microanalysis System and Semafore Digitizer detector that operated at 25 kV. The optical transmittance of the AGIT films deposited on soda-lime glass substrate was measured by PerkinElmer Lambda 45 model UV/vis spectrometer at room temperature to determine the band gap of the AGIT layer. The device characteristics of the fabricated In/p-AGIT/n-Si/Ag heterojunction structures were investigated by carrying out the temperature-dependent dark current–voltage (I–V), capacitance–voltage (C–V) measurements. These measurements were performed with the computer-controlled measurement setup and a Keithley 2401 sourcemeter, Hewlett Packard 4192 A LF model impedance analyzer, the Model 22 CTI Cryogenics closed-cycle helium refrigeration system and the temperatures of the sample and the substrate heater was monitored by LakeShore DRC-91C temperature controller.

3. Results and discussion

3.1. Structural, electrical, optical and photocurrent analysis

The atomic ratios of the deposited AGIT films are shown in Table 1. The films are Ag-deficient and Te-rich. This could be because of different vapor pressures and the segregation coefficients of the constituent elements.

The surface roughness morphology of the AGIT films was investigated by AFM analysis. As seen from Fig. 1 for typical sample, the measured surface roughness is almost uniform with the value of 16.4 nm. The obtained X-ray diffraction patterns for the films show that they have polycrystalline characteristics corresponding to a tetragonal AGIT structure with a strong preferred orientation along with (112) plane direction at $2\theta \sim 24.4°$ (see Fig. 2).

However, the film has binary Ga_2Te_5 crystal phase $2\theta \sim 27.5°$ [17]. All of the as-grown films at substrate temperature of T_S = 200 °C are in polycrystalline nature with Ga_2Te_5 phase. Although some elements according to EDXA are present in excess as compared to their ideal stoichiometry, no metallic elements were detected. The secondary phases in the quaternary structure are originated from the partial reaction of the constituent excessive elements of In, Ga and Ag with Te during the evaporation of the crystalline source. Furthermore, the detailed structural and compositional analyses of AGIT

Table 1
EDXA results for crystal powder and AGIT films.

	Ag (at%)	Ga (at%)	In (at%)	Te (at%)
Powder	29	13	12	46
AGIT	13	11	14	62